DESIGN OF AN INTERNAL MODEL CONTROLLER FOR BINARY DISTILLATION COLUMN

A THESIS

SUBMITTED IN PARTIAL FULFILMENT OF THE

REQUIREMENT FOR THE DEGREE OF

MASTER OF TECHNOLOGY

IN

ELECTRONICS & INSTRUMENTATION

BY

RAKESH KUMAR MISHRA

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Department of Electronics and Communication Engineering

National Institute of Technology

Rourkela-769 008, India

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UNDER THE GUIDANCE OF

PROF. TARUN KUMAR DAN

Department of Electronics and Communication Engineering

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Department of Electronics & Communication Engineering

National Institute of Technology Rourkela

CERTIFICATE

This is to certify that the thesis entitled, "**Design of an Internal Model Controller for Binary Distillation Column**" submitted by **Mr. Rakesh Kumar Mishra** in partial fulfilment of the requirements for the award of Master of Technology Degree in Electronics and Communication Engineering with specialization in **"Electronics & Instrumentation"** during session 2011-13 at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any degree or diploma.

....

Prof. Tarun Kumar Dan

Date: **Associate Professor**

Place: **ECE Department**

NIT Rourkela

Dedicated to My Family and

My Respected Teachers

Specially Prof. T. K. Dan

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Rakesh Kumar Mishra

211 EC3314

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ABSTRACT

In this report Internal Model Control, Lead- Lag based Internal Model Control and modified Internal Model Control for distillation column has been proposed. The prime objective of any industrial process is to perform efficiently with optimum cost reduction. Internal Model Control (IMC) is a commonly used technique that provides a transparent mode for the designing and easy tuning of control structure . I have designed the internal model control for binary distillation column .The transfer function has been taken from Wood and Berry model. The internal model control has been designed considering three strategies namely, process perfect, process mismatch with disturbances and process model with considering only disturbance. It has also been tried to reduce the disturbance created in the system by varying tuning parameter (λ).

In the second proposal, Lead-Lag based Internal Model Control method is proposed based on Internal Model Control (IMC) strategy. We have also designed the Lead-Lag based Internal Model Control for binary distillation column. We have found the composition control and disturbance rejection using Lead-Lag based IMC and comparing with the response of generalize Internal Model Controller.

Finally we have design the Modified Internal Model Structure, and find the response for binary distillation column and compare with generalize Internal Model Controller response.

This thesis presents an Internal Model Control, lead- lag based internal model control and modified internal model control strategy for binary distillation column and comparing the response with each other. The aim is to provide a best strategy to control the distillation column that is favourable in terms of industrial implementation. I have used matlab software to simulate the all process.

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CHAPTER 1

INTRODUCTION

CHAPTER 1
Introduction

1.1 Background

Distillation is most commonly used separation technology in the petroleum and chemical industries for purification of final products. It is not only use for separation but also used for enhancing mass transfer and transferring heat energy. A general distillation column consists of a vertical column, where plates or trays are used to increase the component separations. Reboiler and condenser are used as heat duties. Condenser is used to condense distillate vapor and reboiler is used to provide heat for the necessary vaporization from the bottom of the column. Condensed vapor is collected in reflux drum and require amount of it is used as a reflux. Normally distillation control is based on constant pressure assumption. But due to pressure fluctuation, it is difficult to maintain the stability of system and maintain the purity. The L-V (Liquid-Vapour) structure [6] is known as the energy balance structure and can be considered as the standard control structure for a dual composition control distillation.

Internal Model Control (IMC) is a commonly used technique that provides a transparent mode for the designing and tuning of various types of control architecture. Simultaneously it allows good set point tracking along with sulky disturbance response especially for the process with a small time-delay or time-constant ratio. But for many process control applications, disturbance rejection for the unstable process is of extreme priority than the set point tracking. Hence the controller design that emphasizes disturbance rejection rather than the set point tracking is an important criterion that must be taken into consideration. Internal model control is an advance control technique in which process model is used in order to compute the value of control variable. In internal model control process model is connected in parallel with the actual process, with the help of this we compare both of process. [5]

1.2 Motivation:

Model based control such as model predictive control and internal model control are used in process control industries to controlling the process variable for different process.IMC is most commonly applied advanced control technique because it has only one tuning parameter hence using this we have easily control the process. Distillation columns have been widely used in chemical plants for separation process. The high nonlinearity and dynamic behavior of the column make them hard to control. One of the model based control strategy, Internal Model Control (IMC) is become the central of research to control such column. Many implementations of IMC in the continuous distillation column were based on linear model, using binary components distillation system and tested in the simulation environment. Thus, the implementation of nonlinear based IMC using multi components distillation system is still open for research.[15][32]

1.2 Literature Review

1.2.1 Internal Model control for Distillation Column

For binary distillation column there are several control method is used for controlling the process output and reduce the disturbance .Designing the several control method for distillation column is great challenge in process control instrumentation field. There are different advantage and disadvantage for using various control method in process control industries.

Model based control strategy is new control approach used in process control. There are two model based control which is generally used in control. 1. Model Predictive Control 2. Internal Model Control, Here my project is based on internal model control strategy.

Alina, et al. [17] proposed a distillation column using second order system in which they design the Internal Model Control method using static control law for distillation column. They presented a solution for controlling a binary distillation column from a catalytic cracking unit, using an adaptable internal model control method. They were defined the different performance of Nonlinear Adaptable Internal Model Control (NAIMC) and non-Adaptable Internal Model Control (nAIMC).

Chen, et al. [18] proposed a modified structure of internal model control for unstable process with time delay. They were design new structure using combination of feedback. feed forward, cascade and IMC control strategy.

Tham, et al. [20] proposed the designing procedure of internal model control method. He was defined the IMC strategy, basic principal, IMC based PID control design approach.

Muhammad, et al. [15] proposed the implementation of IMC in controlling continuous distillation column for the past 28 years. There are several models used as IMC is reviewed and highlighted. Further, the past implementation of IMC weather in real application or simulation based is also reviewed. It is found that many implementations of IMC in the continuous distillation column were based on linear model, using binary components distillation system and tested in the simulation environment. Thus, the implementation of nonlinear based IMC using multi components distillation system is still open for research.

Luyben, et al. [16] proposed the transfer function of distillation column. He was proposing the first and second order transfer function for distillation column. He was also developed an ATV method to determine the transfer function for nonlinear multivariable systems.

Wassick, et al. [19] proposed Multivariable Internal Model Control for a Full-Scale Industrial Distillation Column in which he was developed technique of reduced- order controller design for non minimum- phase systems and a modified feed forward IMC structure for simplified decoupling.

1.3 Thesis Outline

Chapter-1 Introduction

Chapter -2 Study of Controllers

This chapter deals with introduction of different controllers which is use in process control field .Several controller such as feedback , feed forward ,cascade, model predictive control and internal model control are explain briefly.

Chapter-3 Study of distillation Column

This chapter deals with introduction of distillation column basic structure and terminology construction stage. McCabe Thiele method used to find number of tray.

Chapter-4 Study of IMC, Lead- Lag based IMC and Modified IMC

This chapter deals with basic concept of internal model control (IMC), block digram of IMC, designing of imc , design of lead-lag based IMC and introduction of modified internal model control (MIMC) .

Chapter-5 Design Parameters & Implementation

This chapter deals with design parameters of internal model control, Lead lag based IMC and modified internal model control. Some process of distillation column is also cover in this section. Implementation of IMC, Lead-Lag based IMC and Modified IMC using MATLAB Programming is given in that chapter.

Chapter-6 Conclusion and scope for future work

The concluding remarks for all the chapters are presented in this chapter. It also contains some future research topics which need attention and further investigation.

CHAPTER 2

CONTROLLERS DESIGN

CHAPTER 2

Controllers Design

This chapter examines the various emerging controller with their applications and highlights the importance of these controller for different process. It further describes the controller's response for different process. Control system is a device, or set of devices to manage, command, direct or regulate the behaviour of other device(s) or system(s). Industrial control systems are used in industries in which several controllers are use for controlling the process variable.

2.1 Feedback Control System:

The block diagram of feedback control system is given fig.1

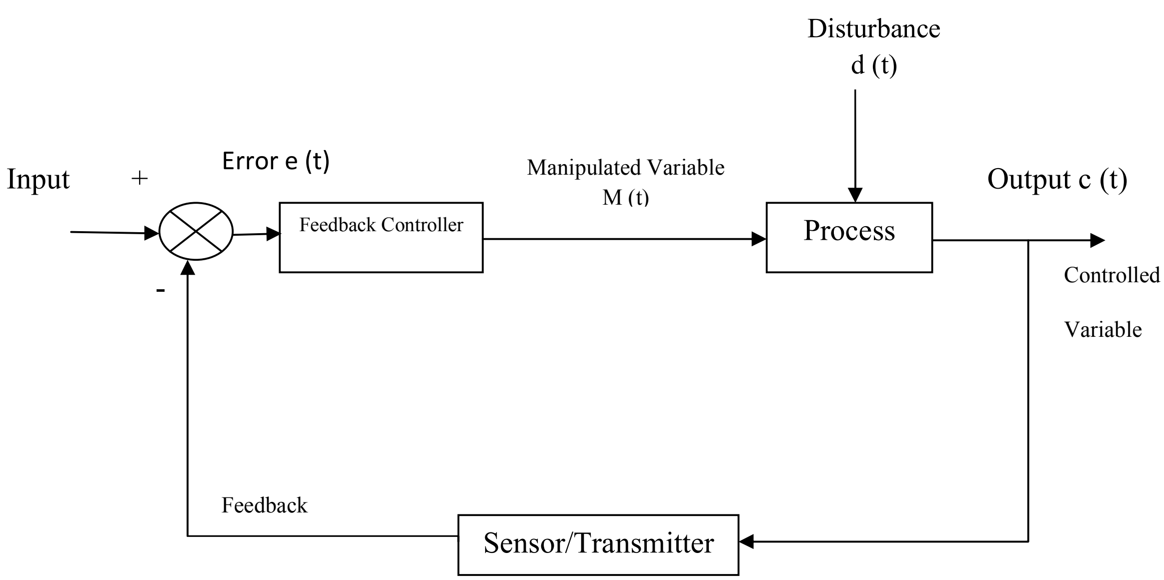

Fig.2.1. Block diagram of feedback control system

Feedback controller is based on feedback control theory. Feedback control is use when un-modelled process disturbance exist. There is several advantage of feedback control system such as it does not require identification and measurement of disturbance. It has no effect of process parameter changes. There are several controller used in feedback configuration which is On-off, P, PI, PID etc. [1]

1.2 Feed forward Control System:

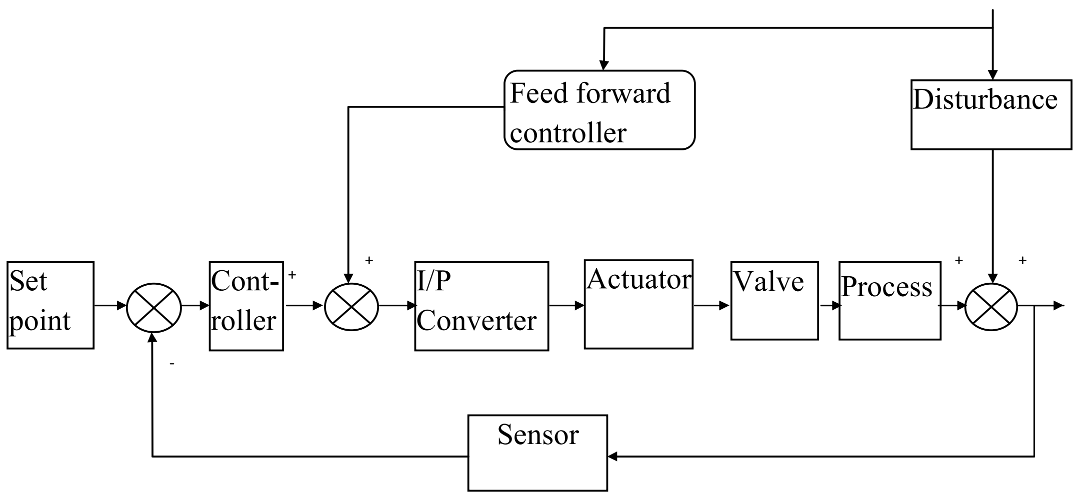

Fig.2.2. Block diagram of feed forward control system

A feed forward control configuration measures the disturbance directly and takes control action to eliminate its impact on the process output. Feed forward control does not introduce instability in closed loop response. This configuration is good for slow systems or with dead time. If physical and chemical properties of the any process are known then feed forward control system is generally used. [1]

1.3 Cascade Control System:

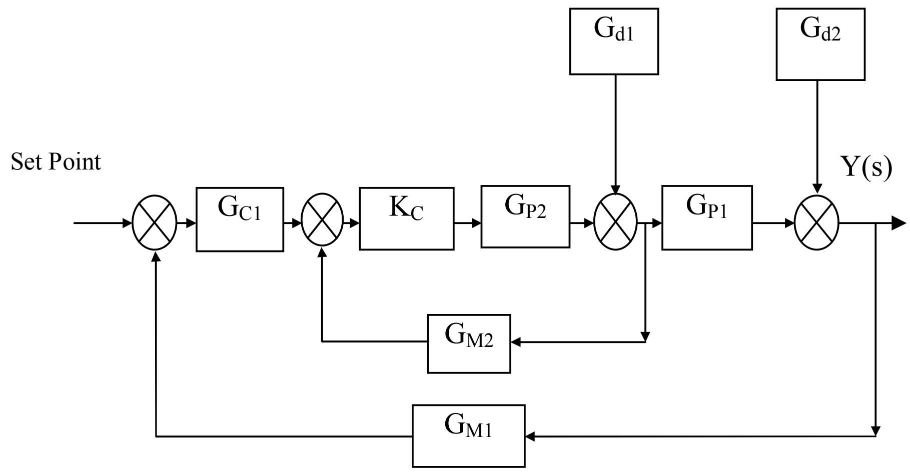

Fig.2.3. Block diagram of cascade control system

In the configuration of cascade control there is more than one measurement and one manipulated variable. In the cascade control to manipulate the secondary controller's set-point it uses the output of primary controller. Its basic principle is that, it is possible to reduce the effect of the disturbance signal before it enters into the primary variable if the secondary variable responds sooner than primary variable to the disturbance. [1] Using cascade control system better control of primary variable occurs, faster recovery from disturbance, improves the dynamic performance and increases the natural frequency of the system this type of advantages occurs. Generally secondary controller is proportional with high gain and primary controller is integral type (PI/PID).

1.4 Model Based Control System:

1.4.1 Model Predictive Control System:

Model predict the future output by considering the difference between actual and predicted output and provide the feedback signal to prediction block which is called as residue[2]. MPC is used for generally multivariable control problem and calculation basis is depending upon current measurement and predicted measurement. [3] Set point is generally called as target. In short, model predict the future output called controlled variable(CV) by considering rate of change in input known as manipulated input (MV) and measured disturbance (DV). MPC has many silent features given as model predicts static and dynamic behaviour of input, output and disturbance variable. In MPC Input and outputs Constraints are systematically considered. Prediction of future output provides an early warning of happening disturbance. Fig-4 shows the block diagram of MPC [2][31].

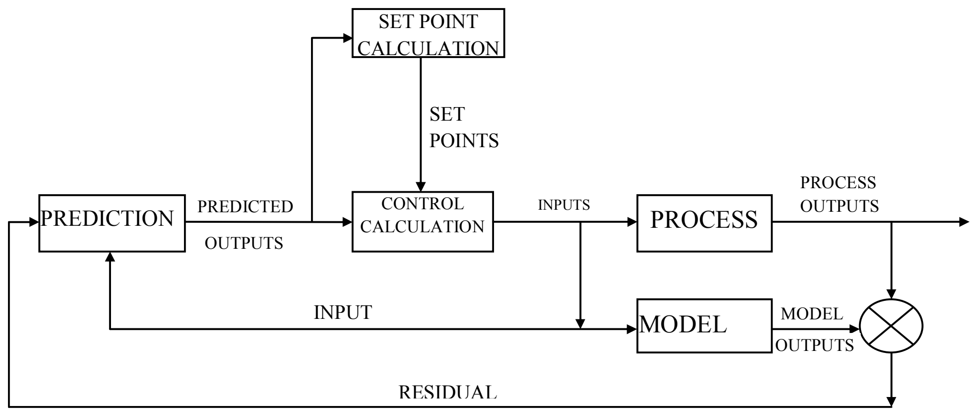

Fig 2.4: Block Diagram of MPC

1.4.2 Internal Model Control System:

The block diagram of internal model control is given below (fig.5). [4] Where Q(s) is the primary controller (IMC) transfer function, $G_p(s)$ is the process transfer function, $G_m(s)$ is the process model transfer function, r(s) is set point, e(s) is error, c(s) is manipulated variable, d(s) is disturbance, $y_m(s)$ is model output and y(s) is controlled variable (process output).

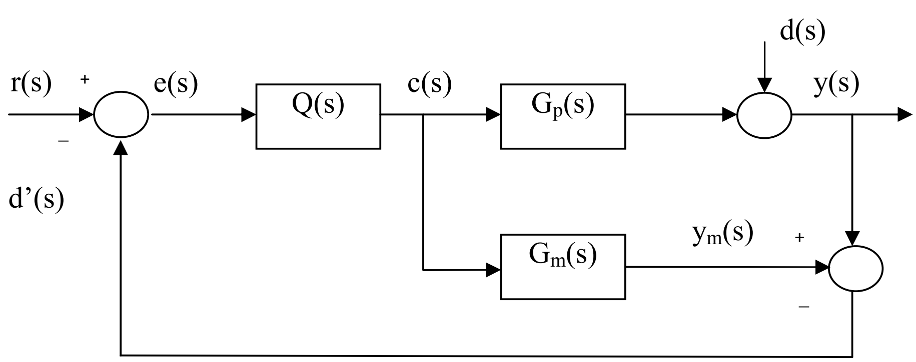

Fig.2.5: Block Diagram of IMC

Internal Model Control (IMC) is a commonly used technique that provides a transparent mode for the designing and tuning of various types of control architecture. Simultaneously it allows good set point tracking along with sulky disturbance response especially for the process with a small time-delay or time-constant ratio. But for many process control applications, disturbance rejection for the unstable process is of extreme priority than the set point tracking. Hence the controller design that emphasizes disturbance rejection rather than the set point tracking is an important criterion that must be taken into consideration. Internal model control is an advance control technique in which process model is used in order to compute the value of control variable. In internal model control process model is connected in parallel with the actual process, with the help of this we compare both of process. [5][9]

CHAPTER 3

INTRODUCTION
OF
DISTILLATION
COLUMN

CHAPTER 3

Introduction of Distillation Column

This chapter deals with the introduction, various parts and working of distillation column which are generally used in petroleum and chemicals industries. Though, there are many kinds of distillation column but we discuss only binary distillation column. Their basic geometries, characteristics and their applications are discussed here.

3.1 Introduction

Distillation is a process in which a liquid or vapour mixture of two or more substances is substances is separated into its component fractions of desired purity by application and removal of heat. Distillation is most commonly used separation technology in the petroleum and chemical industries for purification of final products. It is not only use for separation but also used for enhancing mass transfer and transferring heat energy. A general distillation column consists of a vertical column, where plates or trays are used to increase the component separations. Reboiler and condenser are used as heat duties. Condenser is used to condense distillate vapor and reboiler is used to provide heat for the necessary vaporization from the bottom of the column. Condensed vapor is collected in reflux drum and require amount of it is used as a reflux. Normally distillation control is based on constant pressure assumption. But due to pressure fluctuation, it is difficult to maintain the stability of system and maintain the purity. The L-V (Liquid-Vapour) structure [6] is known as the energy balance structure and can be considered as the standard control structure for a dual composition control distillation.

In this control configuration the vapour flow rate V and the liquid flow rate L are the control inputs. The main objective is to maintain the product concentration i.e., X_B (bottom) and X_D (distillate) due to disturbance F (feed flow) and X_F (feed concentration). Fig-3.1 presents the distillation column [6].

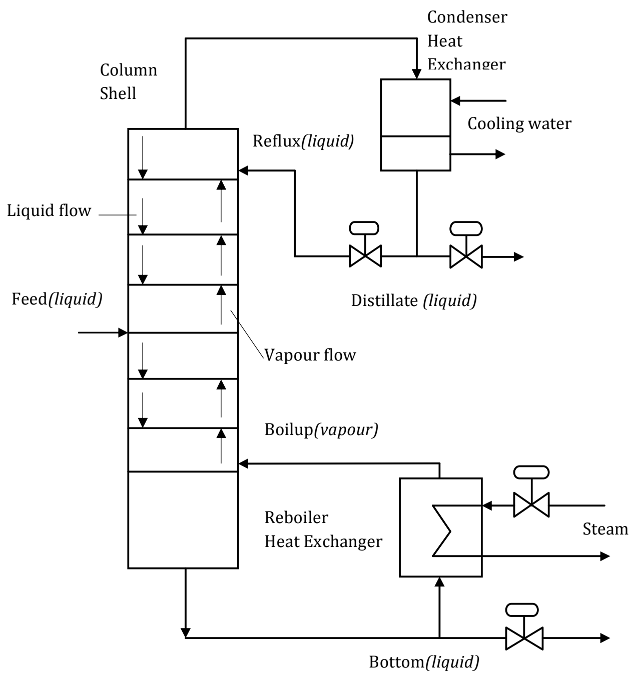

Fig-3.1. Distillation Column

The most of the distillation column is given by first and second order transfer functions with dead time and steady-state gain. Hence we can assume that the transfer function of distillation column is one of the given forms. [7][16]

$$G(s) = \frac{K}{(\tau s+1)^n} e^{-Ds} \qquad n=1,\ 2,\ \text{or}\ 3 \tag{3.1}$$

$$G(s) = \frac{K}{(\tau_1 s+1)(\tau_2 s+1)} e^{-Ds} \qquad n=1\ \text{or}\ 2 \tag{3.2}$$

Where τ, τ_1 and τ_2 are unknown constants.

3.2 Distillation Equipment:

The schematic diagram of a typical distillation column is shown above figure 3.1. The equipment consists of a vertical shell with a number of equally spaced trays mounted inside of the column. Liquid flows through gravity from each tray to other tray below. The vertical shell is connected by suitable piping to a heating device called a reboiler. Reboiler is a part of distillation column which provides the necessary vaporization for the distillation process. The condenser is used to cool and condense the vapor leaving the column from top of the column.

The Reflux drums to hold the condenser vapor from the top of column so that liquid (reflux) can be recycled back to the column. The vertical shell together with the condenser and reboiler constitute a distillation column [6].

3.3. Basic Operation and Terminology:

The liquid mixture that is to be processed is known as the feed and this is introduced usually somewhere near the middle of the column to a tray known as the feed tray. The feed tray divides the column into a top enriching or rectification section and a bottom stripping section, which is given by fig. no. 3.2 & 3.3. The feed which is flows down the column collected at the bottom in the reboiler.

Heat is supplied to the reboiler to generate vapor. The source of heat input can be any suitable fluid, although in most chemical plants this is normally steam. In refineries, the heating source may be the output streams of other columns. The vapor raised in the reboiler is re-introduced into the unit at the bottom of the column. The liquid removed from the reboiler is known as the bottoms product or simply, bottoms. The vapor moves up the column, and as it exits the top of the unit, it is cooled by a condenser. The condensed liquid is stored in a holding vessel known as the reflux drum. Some of this liquid is recycled back to the top of the column and this is called the reflux. The condensed liquid that is removed from the system is known as the distillate or top product.

Thus, there are internal flows of vapour and liquid within the column as well as external flows of feeds and product streams, into and out of the column.

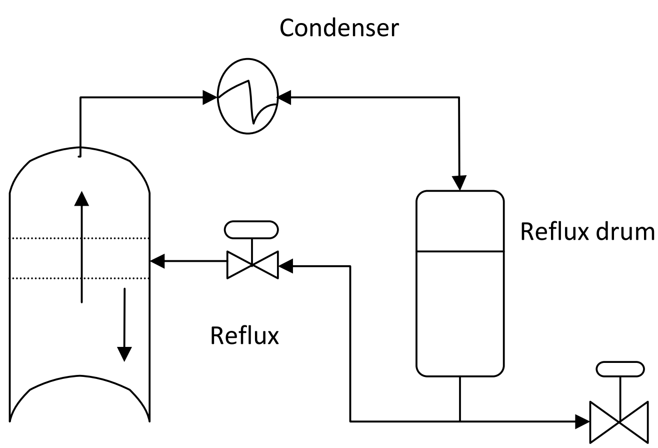

Figure3.2 Enriching (or) rectification section

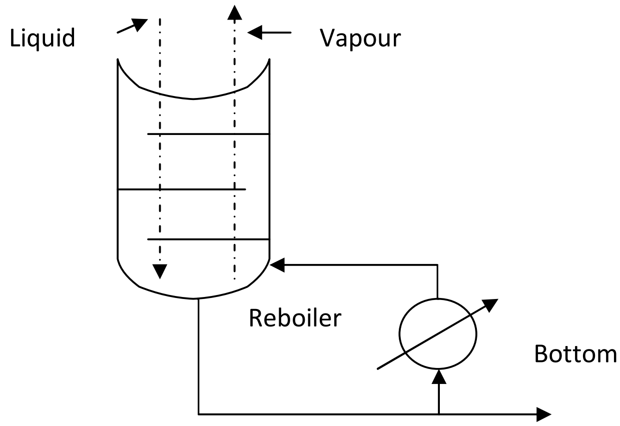

Figure 3.3 stripping section

3.4. Graphical Methods for find no of Tray:

The number of tray distillation column can find either analytical or Graphical method. There are two graphical methods are the Ponchon-Savarit method and McCabe-Thiele method. The equilibrium flash is process in which separation of a binary mixture can be achieved in a single-stage. If enhanced separation is desired, a column containing a suitable number of trays must be used.

Here we only used McCabe-Thiele Method for calculating the number of trays.

3.4.1 McCabe-Thiele Method:

When following conditions are satisfied then this method is used. [6]

1. The molar heats of vaporization of the two substances are the same.
2. Heat effects such as heat of solution, heat losses to and from column are negligible.

These so-called constant-molal overflow assumptions imply that for every mol of vapor condensed, 1 mol of liquid is vaporized. Thus the liquid and vapor rates within each section of the tower remain constant.

The McCabe-Thiele method utilizes material balances and equilibrium relationships. These relationships are written for the enriching section and the stripping section and then combined to solve the binary distillation column. [6]

3.4.1.1 Enriching and Stripping Section:

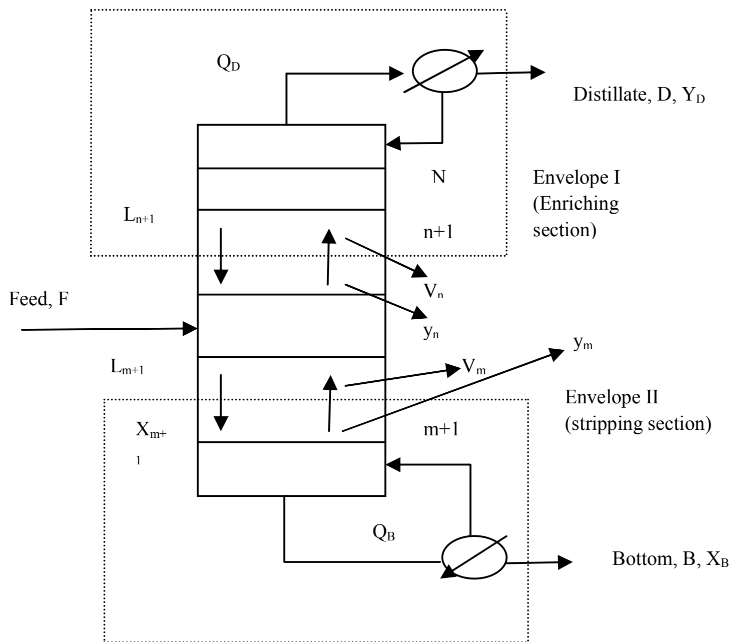

Figure 3.4 Material-balance envelopes for operating lines

According to figure 3.4 for the envelope I enriching section total material balance around a general tray n is given as

$$V_n y_n = L_{n+1} x_{n+1} + D x_D \tag{3.3}$$

The trays are numbered from the bottom up. As per the assumption molal overflow, the subscripts of L and V are dropped. Equation (3.3) may be written as

$$V y_n = L x_{n+1} + D x_D \tag{3.4}$$

Now y_n is given by

$$y_n = \frac{L}{V} x_{n+1} + \frac{D}{V} x_D \tag{3.5}$$

On x-y coordinates equation (3.5) is a straight –line of slope L/V with a y-intercept of X_D D/V. it relates the composition of the more volatile component in the vapor stream leaving a general tray *n* in the enriching section to that of the liquid entering tray *n*. This straight line, which represents the operating line for enriching section of the column shown in Figure 3.5. [8]

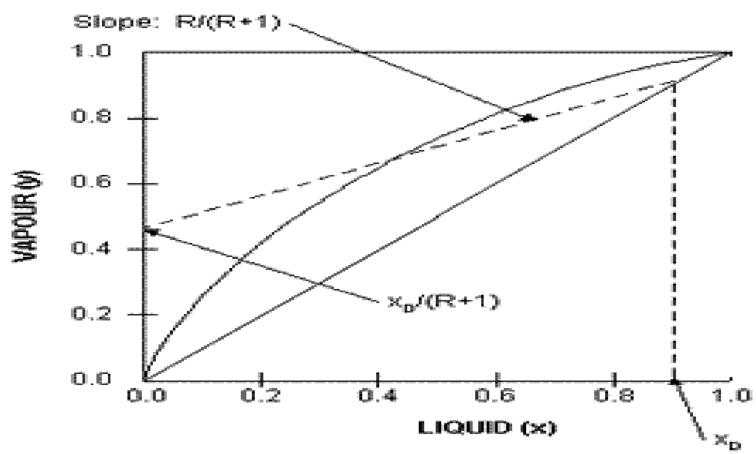

Figure 3.5 Enriching-section operating line

Similarly for the stripping-section the equation of the operating line can be given by component material balance around envelope II in Figure 3.4

$$y_m = \frac{\bar{L}}{\bar{V}} x_{m+1} - \frac{B}{\bar{V}} x_B \qquad (3.6)$$

In equation 3.6 the bar indicates that the stream is in the stripping section. This equation relates the composition of the more volatile component in the vapor stream leaving tray *m* in the stripping section to that in the liquid entering tray *m.* stripping section operating line has a slope of $\frac{\bar{L}}{\bar{V}}$ and it intersects the diagonal, where x=y, at X_B which is given in Figure 3.6.[8][6]

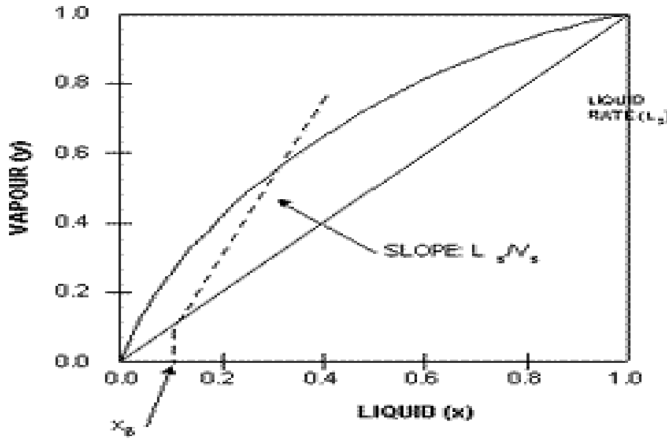

Figure 3.6 stripping-section operating line

3.4.1.2 Construction of a Stage:

The operating line, which is generally use the equation of stripping section or enriching section, is used in conjunction with curve to locate equilibrium curve to locate an equilibrium stage on an x-y diagram as shown in Figure 3.7 [8]

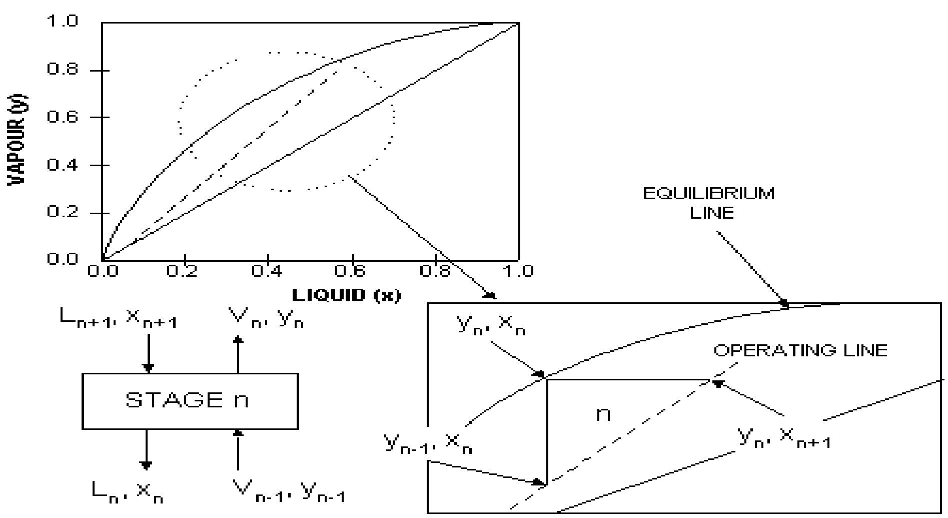

Figure 3.7 construction of stage

A point on the operating line gives x_{n+1}, y_n corresponding to the composition of the two streams L_{n+1}, V_n passing stage *n*. Thus the triangle shown in Figure 3.7 represents stage n.

This type of graphic construction will be necessary to determine the number of ideal trays required for a specified separation.

The enriching-section operating line intersects the stripping-section operating line at the feed tray. The equation of the feed line at which these two lines intersect may be derived by combining the material-balance equations for the feed tray:

$$\bar{L} = L + qF \tag{3.7}$$

And

$$\bar{V} = V - (1 - q)F \tag{3.8}$$

Where q=fraction of feed that is liquid

Depending on the state of the feed, the feed lines will have different slopes. For example,

$q = 1$ (saturated liquid)

$0 < q < 1$ (mix of liquid and vapor)

$q > 1$ (sub cooled liquid)

$q < 0$ (superheated vapor)

$q = 0$ (saturated vapor) [6]

The q-lines for the various feed conditions are shown in Figure 3.8. [8]

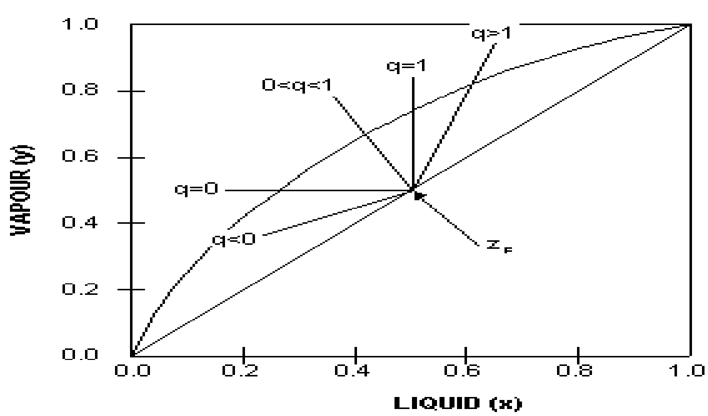

Figure 3.8 Feed lines

Enriching- and stripping-section operating line equations are given as

$$Vy_n = Lx_{n+1} + Dx_D \tag{3.5}$$

And

$$\overline{V}y_m = \overline{L}x_{m+1} - Bx_B \tag{3.6}$$

These two lines intersect at a point where the x's and y's become identical. By subtracting equation (3.6) and equation (3.5) we find

$$(V - \overline{V})y = (L - \overline{L})x + Dx_D + Bx_B \tag{3.9}$$

The equation (3.9) can be written in the view of equation (3.7) and (3.8) as

$$(1 - q)Fy = -qF_x + Fz_F$$

Or

$$y = \frac{q}{q-1}x - \frac{z_F}{q-1} \tag{3.10}$$

The equation (3.10) is the equation of the feed line having a slope of q/q-1 and an intercept on the x=y diagonal al z_F. The q lines for the various types of feed are shown in Figure 3.8. For an optimum design that requires the fewest number of stages, the feed tray must be placed at the correct location. To determine the number of stages required for a specified separation, the procedure is to locate x_D, x_B, z_F on the diagonal; draw the feed line; the enriching-section operating line, and the stripping-section operating line; and then step off the stages. [6]

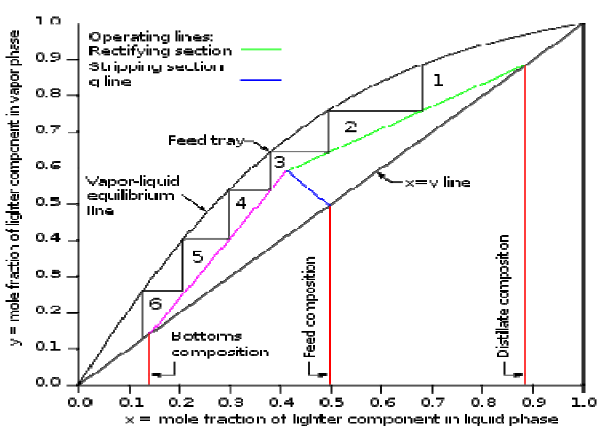

Figure 3.9Typical McCabe-Thiele plot

CHAPTER 4

INTERNAL MODEL CONTROL

CHAPTER 4

Internal Model Control

This chapter deals with the basic principal, designing procedure, different strategy and block diagram of Internal model control, lead-lag based internal model control and modified internal model control.

4.1 Introduction

In industrial system, internal model control and model Predictive control (model based control) has proven to be successful controller design strategies.Internal Model Control (IMC) is a commonly used technique that provides a transparent mode for the designing and tuning of various types of control architecture. Simultaneously it allows good set point tracking along with sulky disturbance response especially for the process with a small time-delay or time-constant ratio. But for many process control applications, disturbance rejection for the unstable process is of extreme priority than the set point tracking. Hence the controller design that emphasizes disturbance rejection rather than the set point tracking is an important criterion that must be taken into consideration. Internal model control is an advance control technique in which process model is used in order to compute the value of control variable. In internal model control process model is connected in parallel with the actual process, with the help of this we compare both of process [5].Hear, to design a liner controller based on a linearized model for chemical processes all model based control strategies is used. Compare to open loop control, internal model control is able to compensate for disturbance and model uncertainty. Internal model control provides a useful range of all stable controllers for open loop stable systems [9]. For the perfect model assumption, the design of a stable internal model control becomes an insignificant task for close-loop stability. Although most of the process is nonlinear in nature, the internal model controller performs acceptable result for this process.

4.1.1 Basic Principal

Model based control systems such as model predictive control and internal model control are often used to set point tracking and rejection of low disturbances for process control applications. The internal model control (IMC) theory relies on the internal model principle which states that if any control system contains within it, some representation of the process to be controlled then a perfect control is easily achieved. In particular, if the control scheme has been developed based on the exact model of the process then perfect control is theoretically possible.[10]

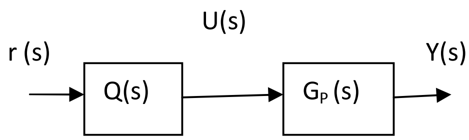

Fig. 4.1 Open loop control strategy

Where $G_P(s)$ is actual process or plant, Q(s) is controller of the process, r(s) is set point, u(s) is manipulated variable and y(s) is controlled variable (process output).

$$y(s) = Q(s)\, G_P(s)\, r(s) \qquad (4.1)$$

Now we take process model $G_m(s)$

A controller Q(s) is used to control the process Gp(s). Suppose G_m (s) is the model of Gp(s) then by setting:

$Q(s)$ =inverse of $G_m(s)$ (4.2)

And if

$Gp(s) = G_m(s)$ (the model is the exact representation of the actual process)

Now it is clear that the output will always be equal to the set point when these two conditions certified. According to this when we have complete knowledge of process (as enclosed in the process model) being controlled, we can achieve perfect control.

Although the IMC design procedure is identical to the open loop control design procedure, the implementation of IMC results in a feedback system. Hence, compare to open loop control IMC is able to compensate for disturbances and model uncertainty. IMC must be detuned to assure stability if there is model uncertainty.

4.1.2 Block Diagram of IMC

The block diagram of internal model control is given fig. 4.2. The distinguishing characteristic of this structure is the process model, which is in parallel with the actual process. [4][9]

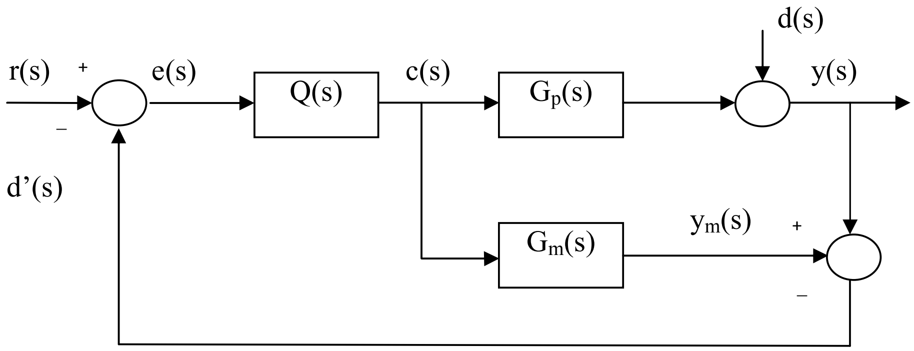

Fig 4.2: Block Diagram of IMC

Where Q(s) is the primary controller (IMC) transfer function, $G_p(s)$ is the process transfer function, $G_m(s)$ is the process model transfer function, r(s) is set point, e(s) is error, c(s) is manipulated variable, d(s) is disturbance, $y_m(s)$ is model output, d'(s) represent estimated disturbance and y(s) is controlled variable (process output).

4.1.3. The IMC strategy

There are three IMC strategies. [10]

4.1.3.1 Model is Perfect and no Disturbance:

If the model is perfect which gives $G_P(s) = G_m(s)$ and there are no affect of disturbance (d(s) =0) then according to fig. 4.2 feedback signal become zero. Hence relationship between r(s) & y(s) is given as

$$y(s) = G_P(s)\, Q(s)\, r(s) \tag{4.3}$$

This is equivalent to equation 4.1 open loop control system design.

4.1.3.2 Model is Perfect and Disturbance Affect the Process:

If the model is perfect which gives $G_P(s) = G_m(s)$ and there is disturbance hence feedback signal is d'(s) = d(s) then output is given by

$$y(s) = [1 - G_m(s)Q(s)]d(s) \tag{4.4}$$

$$d(s) = G_d(s)\, l(s) \tag{4.5}$$

l(s) is load disturbance.

4.1.3.2 Model Uncertainty and no Disturbance:

When there are no disturbances (d(s)) but model uncertainty ($G_P(s) \neq G_m(s)$) occurs then feedback signal is

$$d'(s) = [G_P(s) - G_m(s)]\, u(s) \tag{4.6}$$

Hence process output

$$y(s) = \frac{G_p(s)Q(s)}{1+Q(s)(G_p(s)-G_m(s))} r(s) + \left[\frac{1-G_m(s)Q(s)}{1+Q(s)(G_p(s)-G_m(s))}\right] d(s) \tag{4.7}$$

4.1.4. The IMC Design Procedure:

We know that dynamic controller gives faster response than the static controller so we use dynamic control law. [10]

Hence

$$Q(s) = \frac{1}{G_P(s)} \tag{4.8}$$

This is only valid with stable process with no time delay. Now we have focus to design the IMC for time delay system.

The controller design procedure has been generalized to the following step [10][32].

1. First we have identified the process model into invertible (good stuff) and noninvertible (bad stuff which is defined when time delays and RHP zeros) by using all pass formulation or using simple factorization.
2. Invert the (good stuff) invertible portion of the process model and to make proper add the filter.

$$Q(s) = \frac{1}{G_{m-}(s)} f(s) \tag{4.9}$$

Where f (s) = $\frac{1}{(\lambda s+1)^n}$ is filter and n is constant (123…..n) and chosen to make the controller proper or semi proper.

4.2 Lead-Lag based Internal Model Control

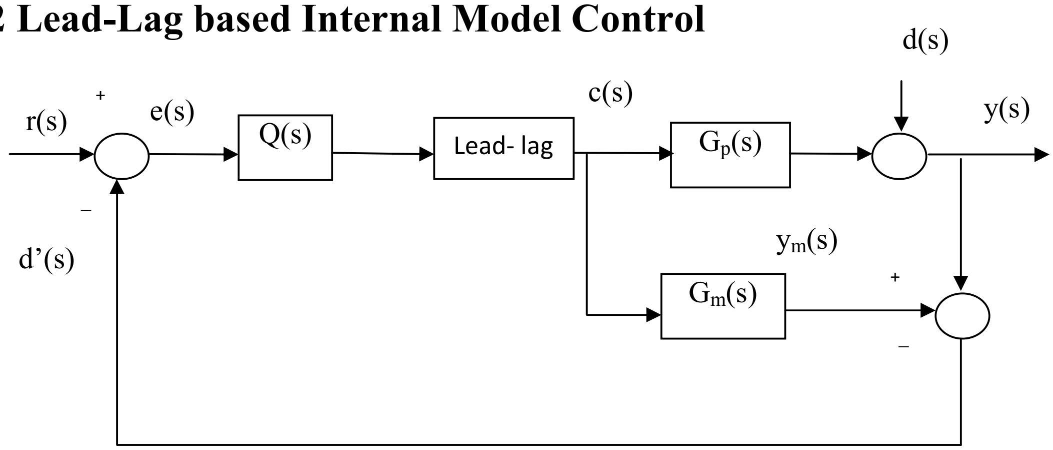

Fig 4.3: Block Diagram of Lead-Lag based IMC

The fig.4.3 shows the block diagram of lead-lag based internal model control. Lead- Lag based internal model control design method is similar to generalized IMC design procedure, here I have only introduced lead-lag network. As we know that lead network stabilized the system, increase the speed of response, improve the transient response and lag network decrease the steady state error, increase the accuracy hence I introduced lead-lag network with internal model control.

Lead-Lag transfer function given by

$$T(s) = \frac{\alpha s + 1}{\beta s + 1} \tag{4.10}$$

Internal model controller from equation 4.9

$$Q(s) = \frac{1}{G_{m-}(s)} f(s)$$

Hence lead-lag based IMC

$$Q'(s) = \frac{f(s)}{Gm-(s)} \frac{\alpha s + 1}{\beta s + 1} \tag{4.11}$$

Where α and β are time constant and used as a tuning parameter for lead-lag based Internal Model Controller. Here lead lag based IMC there are three tuning parameter α, β and f (s) = $\frac{1}{(\lambda s+1)^n}$ is filter and n is constant (123…..n) and chosen to make the controller proper or semi proper.

4.3 Modified Internal Model Control

I have developed a new structure for controlling and disturbance rejection of binary distillation column. The block diagram of modified internal model control is given below in fig.4.4. In which I have used cascade, feed forward-feedback and IMC controller for developed the structure. Here IMC (K_{imc}) can use for set point tracking, feed forward-feedback controller (K_2) can be used for disturbance rejection and cascade control loop controller use for suppressing disturbance. Using these types of controllers I have design modified internal model control (MIMC). [18]

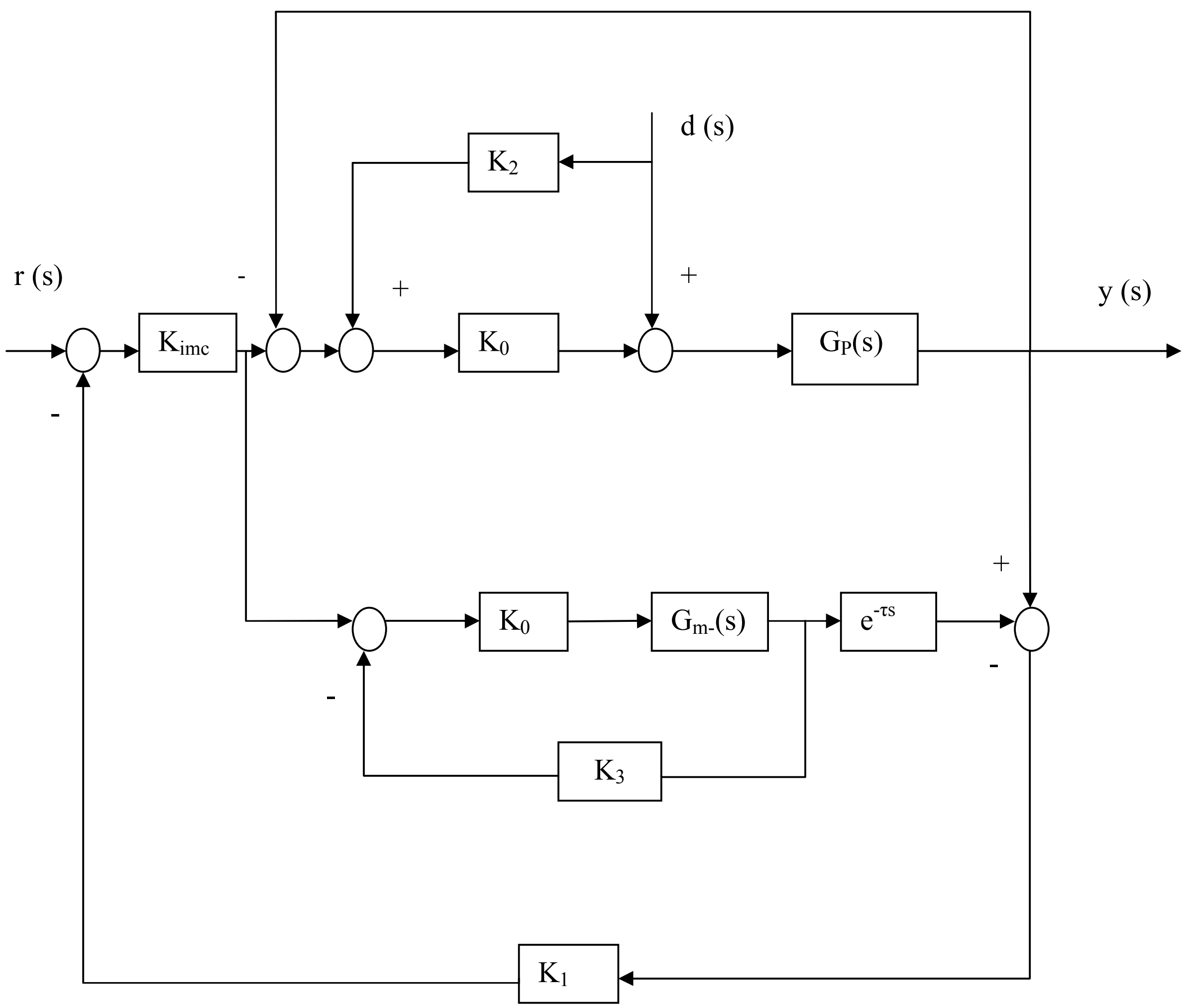

Fig 4.4: Block Diagram of Modified internal model control

Where K_{imc} is the primary controller (IMC) transfer function, $G_p(s)$ is the process transfer function, $G_{m-}(s)$ is the process model transfer function with invertible part, r(s) is set point, d(s) is disturbance, K_0 is use as cascade controller generally PD (Proportional + derivative), K_1 is filter, K_2 is feed forward controller, K_3 is feedback constant (generally 1) and y(s) is controlled variable (process output).[18]

Some controller parameter is given below.

K_{imc} is transfer function of IMC controller.

$$K_{imc} = \frac{1}{G_{m-}(s)K_0} f(s) \tag{4.12}$$

$$K_0 = K\ (bs+1) \tag{4.13}$$

K_0 is derivative type controller (PD). In which b is derivative constant and K is Proportional constant.

$$K_1 = \frac{1}{(\lambda s+1)^n} \tag{4.14}$$

$K_1$is filter and n =(1 2 3..........n).

K_2 is transfer function of feed forward controller defined as

$$K_2 = \frac{G_d(s)}{G_p(s)} \tag{4.15}$$

Where $G_d(s)$ is disturbance transfer function and $G_P(s)$ is process transfer function.

Hence, $K_2 = -1/K_0$

CHAPTER 5
DESIGN PARAMETERS & IMPLEMENTATION

CHAPTER 5
Design Parameters & Implementation

5.1 Internal Model Control for Binary Distillation Column

Distillation is a separation method in the petroleum and chemical industries for purification of final products. A general distillation column consists of a vertical column, where plates or trays are used to increase the component separations. A condenser is used to cool and condense the vapor and a reboiler is used to provide heat for the necessary vaporization from the bottom of the column. A reflux drum is used to hold the condensed (liquid) vapor to recycle the liquid reflux to back from top of the column. [6]

Distillation column process has two output top X_D (the propylene)and bottom X_B(the propane) composition and four input such as two disturbance feed flow(F) and feed composition (X_F) and two controlled variable reflux(L)and bottom product flow (B).

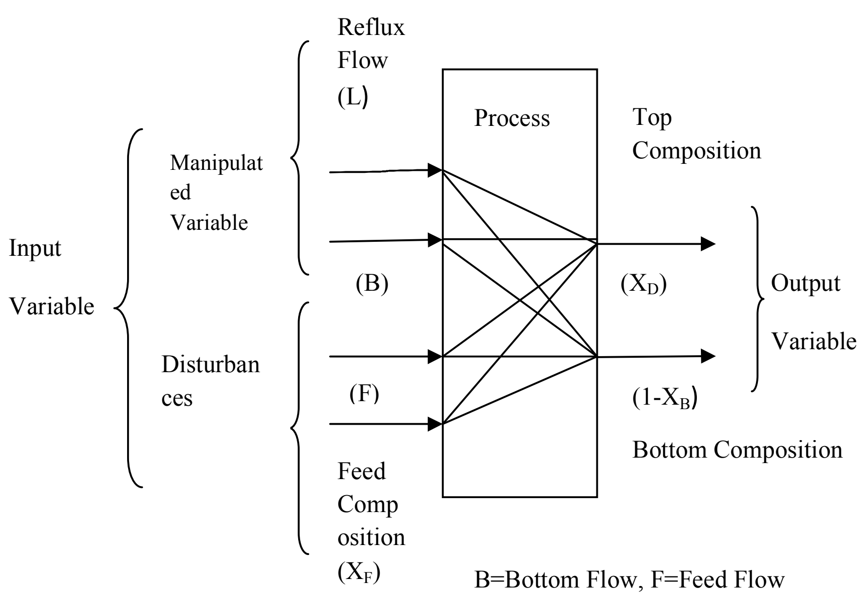

Figure5.1. Distillation process block diagram.

5.1.1 Internal Model Control for II Order Distillation Column

The process model is described by second order transfer function with dead time having gain constant and time constant for process channel. [17][16]

$$Gp(s) = \frac{K_m}{T_2 s^2 + T_1 s + 1} e^{-\tau s} \qquad (5.1)$$

K_m is the process gain, τ is the dead time and T_2 and T_1 are time constants.

The process model is a nonlinear one, represented as a reunion of different transfer functions one for each operating point and process channel, as it is shown in table 1.

Table I: Model Parameters

Channel	**Operating point [mol.fr.]**	**K_m**	**T_2[min^2]**	**T_1[min]**
L-X_D	X_D=0.8	0.01	0.7	30.6
F-X_D	X_D=0.8	−0.004	112.2	581.8
B− (1−X_B)	1−X_B=0.9	−0.009	3.9	144
X_F−(1−X_B)	1−X_B=0.9	−0.0094	5742.5	2200.6

5.1.1.1 MATLAB Implementation and Results:

IMC design and output response for Distillation Column when model is perfect ($G_P(s) = G_m(s)$) and disturbance d(s) =0

5.1.1.1. a Manipulated variable response

Reflux ratio (L)

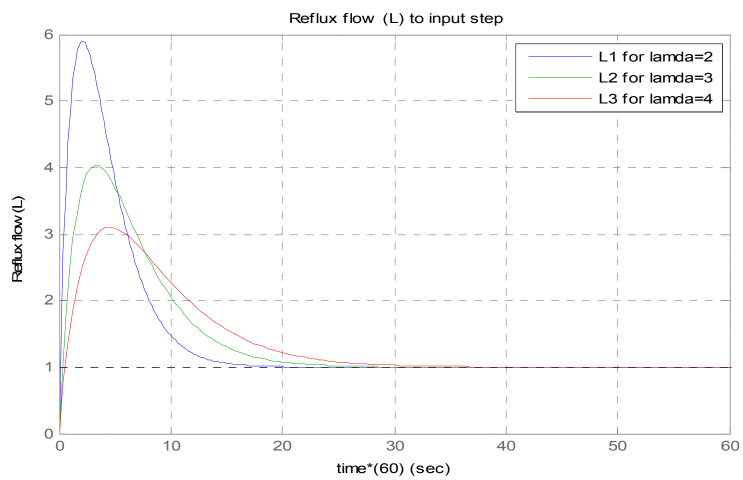

Fig. 5.2 Manipulated Variable Response for top product

Steam flow (S)

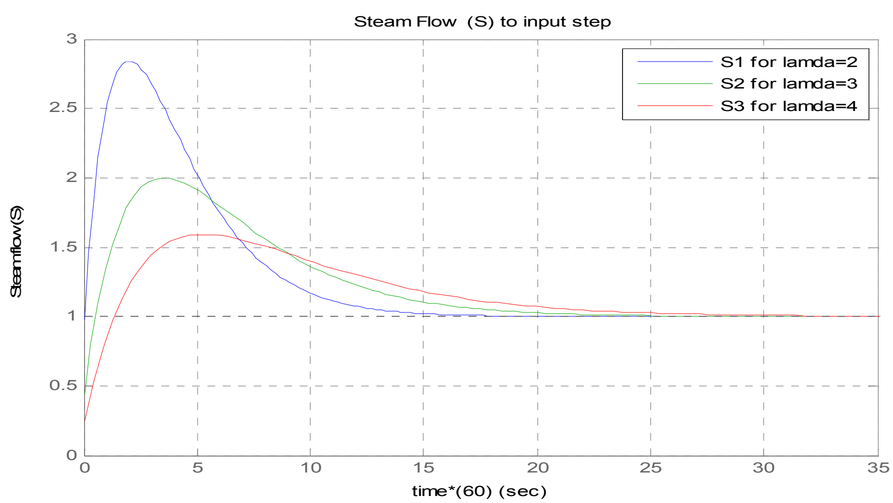

Fig 5.3: Manipulated Variable Response for bottom product

Fig 5.2 shows the controller output (reflux ratio L) for top product and fig5.3 shows the controller output (stem flow S) for bottom product. It shows for increasing the value of lambda (λ) settling time increase and rise time decrease. IMC has advantage that there is only one tuning parameter Lambda and changing the Lambda we can easily find manipulated variable for accurate controlled variable for distillation column. There is only one gain constant so we can easily change manipulated variable for accurate result.

5.1.1.1. b Controlled variable Response:

Using IMC for distillation column we have found very good result of top product & bottom Product. This controller gives offset free control output .There is good set point tracking. As Lambda is increase the output response is slow and by changing the value of lambda. We can find accurate response and disturbance rejection and we can tune the controller by changing gain and lambda.Fig.5.4 and fig.5.5 shows output response of binary distillation column.

Top Product (X_D)

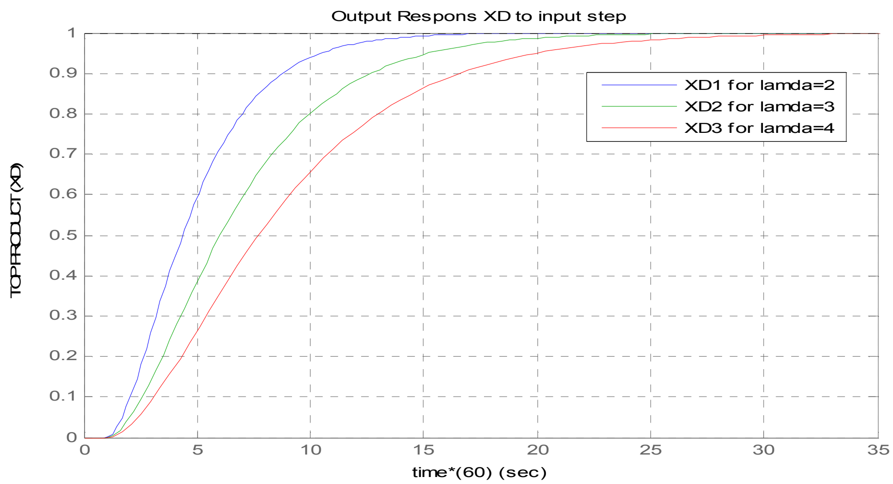

Fig 5.4: Output Response of distillation column Top product

Bottom Product (X_B)

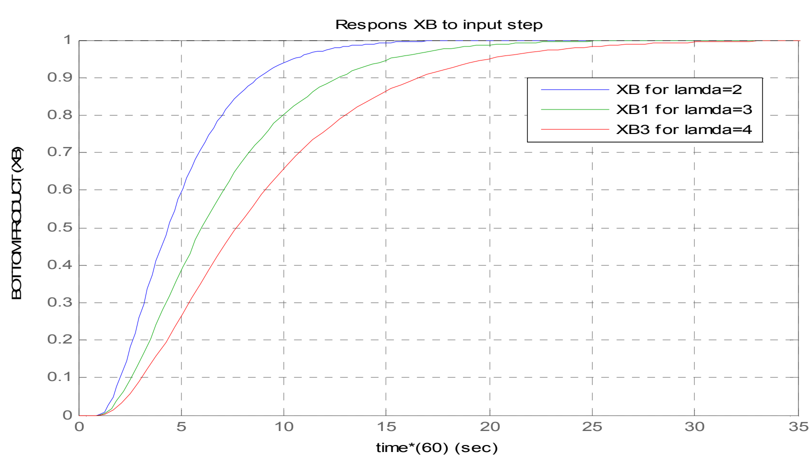

Fig 5.5: Output Response of distillation column Bottom product.

5.1.2 Internal Model Control for Distillation Column

We have taken Wood and Berry 2×2 process. [11]

$$\begin{bmatrix} x_D(s) \\ x_B(s) \end{bmatrix} = \begin{bmatrix} \dfrac{12.8e^{-s}}{16.7s+1} & \dfrac{-18.9e^{-3s}}{21s+1} \\ \dfrac{6.6e^{-7s}}{10.9s+1} & \dfrac{-19.4e^{-3s}}{14.4s+1} \end{bmatrix} \begin{bmatrix} R(s) \\ S(s) \end{bmatrix} + \begin{bmatrix} \dfrac{3.8e^{-8.1s}}{14.9s+1} \\ \dfrac{4.9e^{-3.4s}}{13.2s+1} \end{bmatrix} F(s) \tag{5.2}$$

Where, F = feed of distillation column

X_D = composition of distillation (top)

X_B = composition of bottom

R = reflux flow

S = steam flow

The process model is described by first order transfer function with dead time having gain constant and time constant for process channel.

$$Gp(s) = \frac{K_m}{Ts+1} e^{-\tau s} \tag{5.3}$$

K_m is the process gain, T is the time constant and τ is the dead time.
The process model is a nonlinear and represented by using several parameters given below in table II.

Table II. Model Parameters

Channel	K_m(process gain)	T (time in min.)	τ(dead time)
L-x_D	12.8	16.7	1
F-x_D	3.8	14.9	8.1
S- X_B	-19.4	14.4	3
F-X_B	4.9	13.2	3.4

5.1.2.1 MATLAB Implementation and Results:

a. when model is perfect and no disturbance effect on the process :

Manipulated variable response (reflux ratio L)

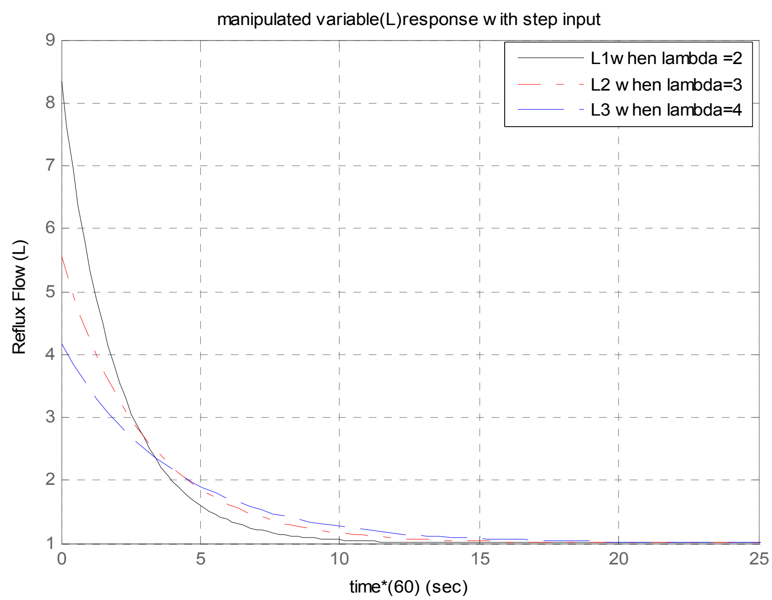

Figure5.6. Manipulated Variable Response (reflux ratio L).

Fig (5.6) shows the controller output for different tuning parameter λ. As λ increases, the manipulated variable response decreases. So we need a proper range of λ for better operation.

Controlled variable response (top product X_D)

Fig (5.7) shows the process output (top product X_D) for different tuning parameter λ. Above result shows that with increase in the value of λ, the set point tracking increases and we find accurate result after a long time, but for small value of λ the transient and saturation time decreases and better set point tracking is achieved. For small values of λ the speed of response increases.

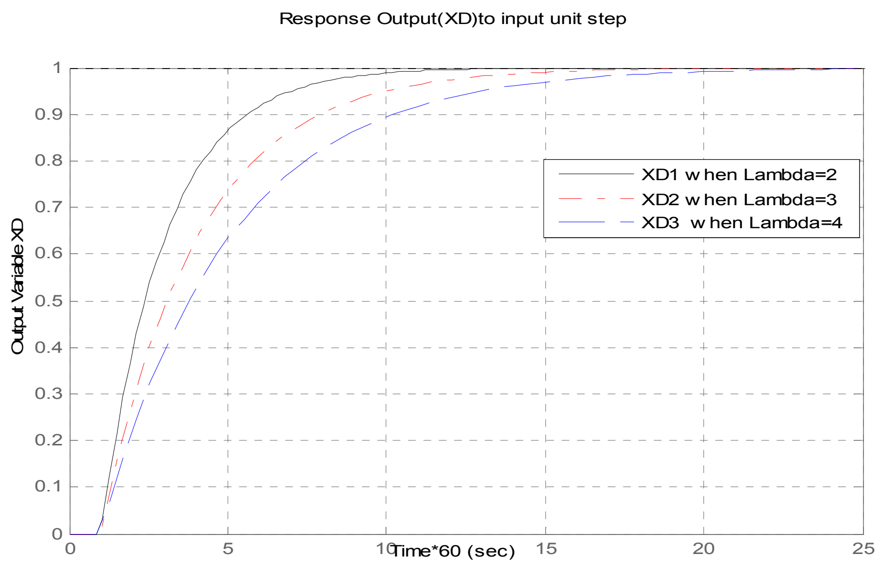

Figure5.7 Output Variable Response (top product X_D).

b. when model is perfect and disturbance is affecting the process

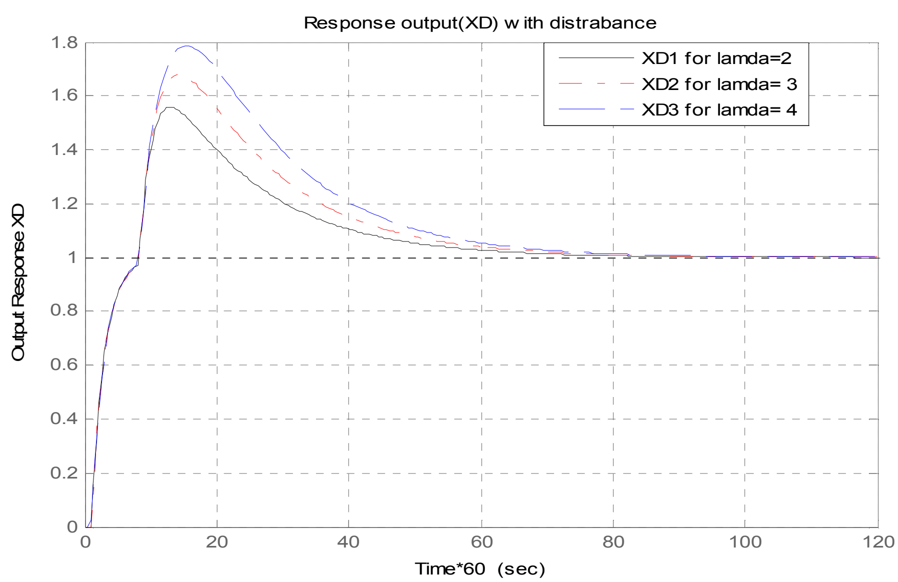

Figure5.8. Output Variable Response with disturbance (top product X_D).

Fig (5.8) shows the result when model is perfect and disturbance is affecting the process. It indicates that when the value of λ increases, peak overshoot and settling time also increases. For small value of λ, spike is small compare to larger values. For small value of λ lambda disturbance less affect the process.

c. Disturbance Rejection

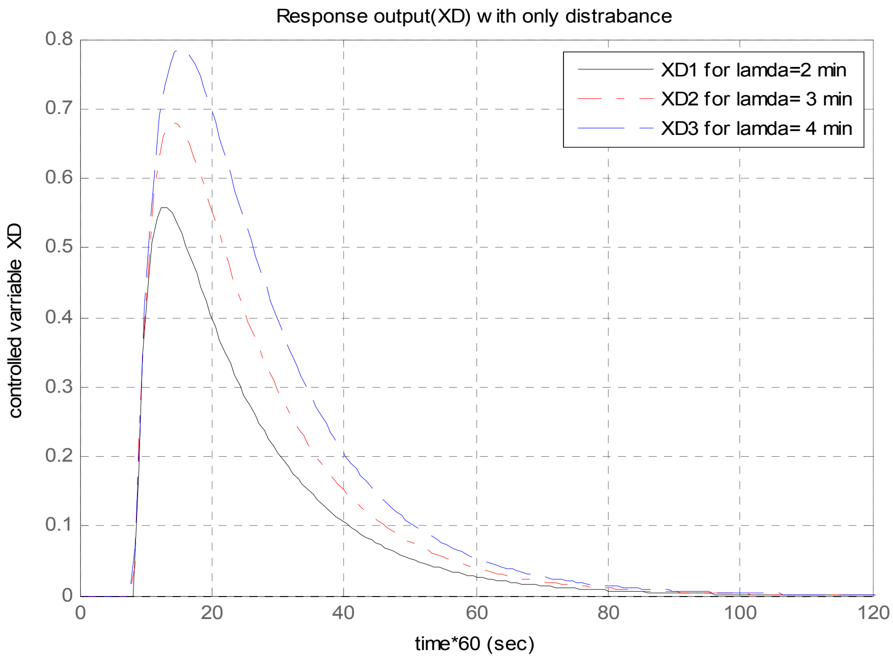

Figure5.9. Output Variable Response with only disturbance (top product X_D)

Fig (5.9) shows the result by considering only disturbance which is affecting the process. Using simple filter f(s) = $\frac{1}{(1+\lambda s)^n}$ and different tuning parameter λ we have tried to remove the disturbance and Taking small value of (λ) lambda disturbance is easily removed from the process.

d. Disturbance Rejection using New Filter [10][32]

$$f(s) = \frac{\Upsilon s + 1}{(1 + \lambda s)^n} \tag{5.4}$$

Where $\Upsilon = \frac{33.4\lambda - \lambda^2}{16.7}$

'ϒ is constant.

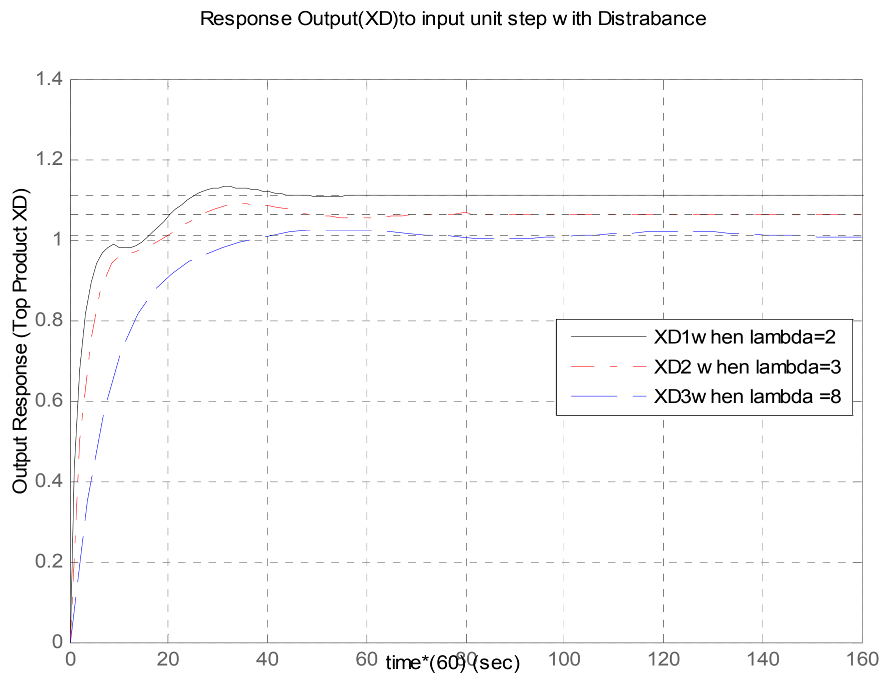

Figure5.10 Output Variable Response Disturbance Rejection (top Product X_D)

Fig (5.10) shows the output variable response. It indicates the rejection of disturbance after introducing the filter with different tuning parameter (λ). The different type of a filter for designing this model controller is given above.

It shows that the disturbance rejection has taken place when λ=8 min. With decrease in λ, the distortion is taking place in control output (X_D) and offset is increased.

5.2 Lead-Lag based Internal Model Control for Binary Distillation Column:

Using equitation 5.3 and table II, I have design the Lead-Lag based internal model control response for binary distillation column.

5.2.1. MATLAB Implementation for Top Product (X_D):

a. When model is perfect and no disturbance effect on the process:

Manipulated variable response (reflux flow L):

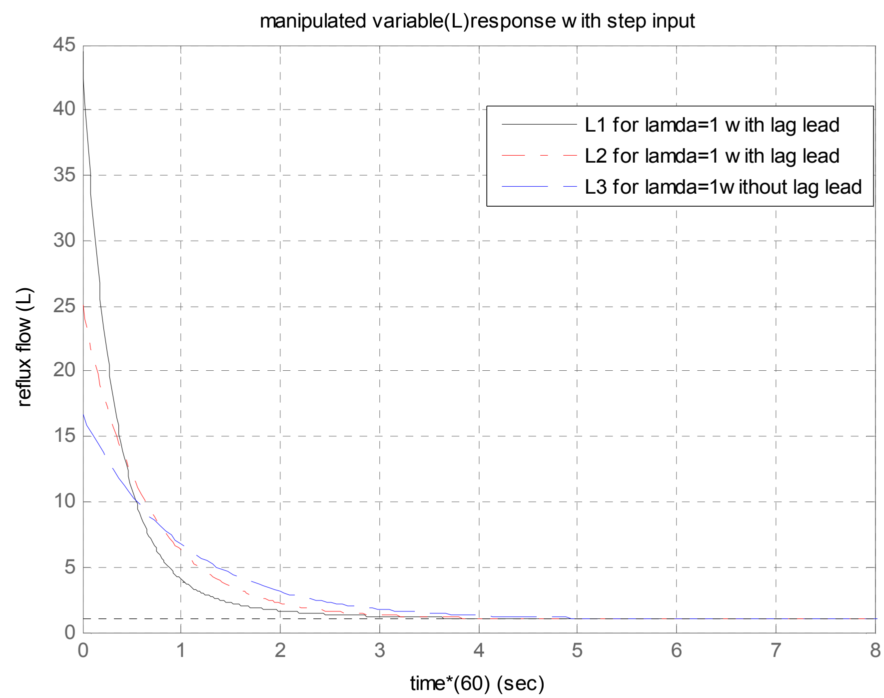

Figure5.11. Manipulated variable response (reflux flow L)

Fig. 5.11 shows the rate of reflux flow (L), which indicates that by using lead-lag based internal model controller response, is accurate, good set point tracking and less settling time as compare to generalize internal model controller response. The lead- lag based internal model controller response approach to critical damped but generalizes internal model controller approach to over damp. Here three tuning parameter is use for find the accurate response. For this λ = 1 minute and α =.3 min. and β= .31min. and For L2 α =.4 min. and β= .41 min. use as a tuning parameter.

Controlled variable response (top product X_D):

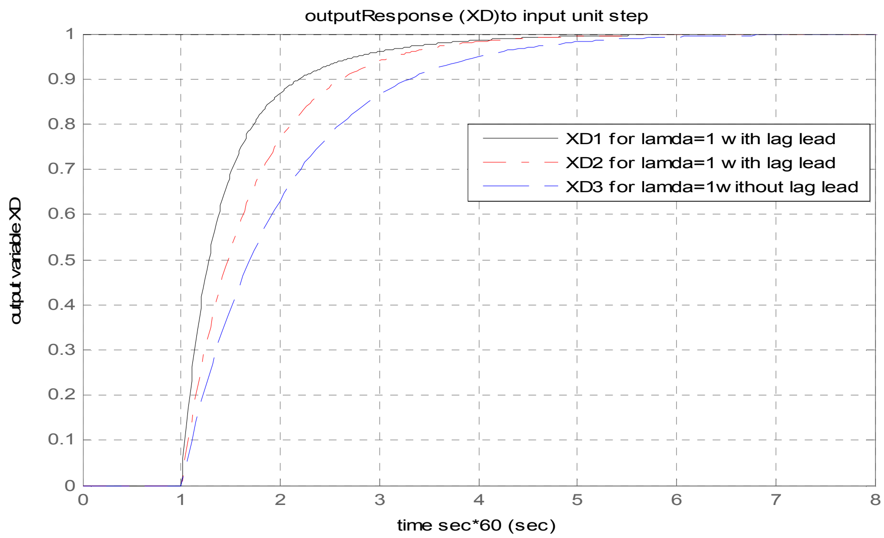

Figure5.12. Controlled variable response (top product XD)

Fig. 5.12 shows the top product (X_D), controlled variable response in using generalized IMC and Lead- lag based IMC. Here I have find for λ=1 min. and different α and β(tuning parameter of lead-lag IMC) lead lag based IMC gives good set point tracking and less settling time. Here I have taken α= .8 min., β = .3 min. and α= .9 min., β=.6 min. as tuning parameter.

b. When model is perfect and disturbance is affecting the process:

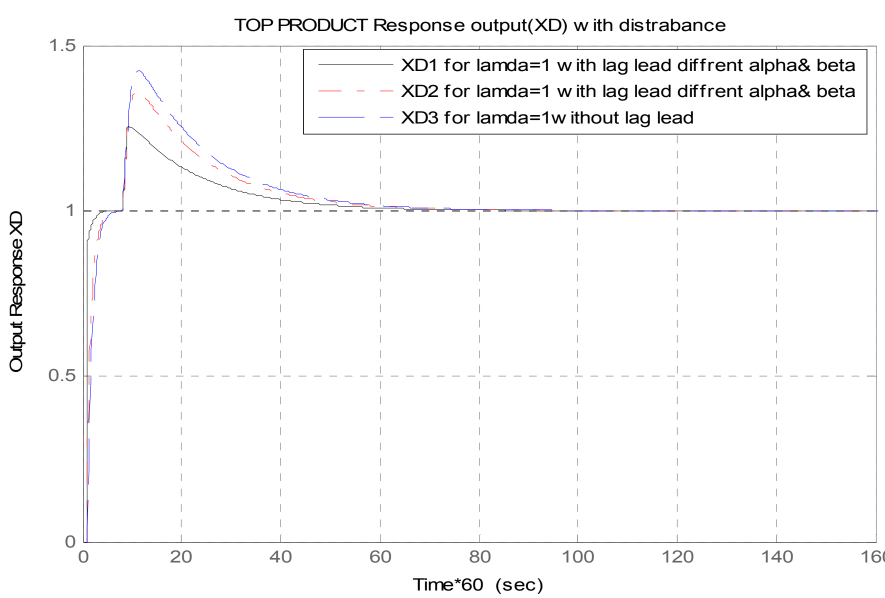

Figure5.13. Controlled variable response with disturbance (top product $X_{D)}$

Fig. 5.13 shows the top product (X_D), controlled variable response with disturbance using generalized IMC and Lead- lag based IMC. Here I have find for λ=1 min. and different α and β(tuning parameter of lead-lag IMC) lead lag based IMC response is less affect to disturbance compare to simple IMC, here I have taken λ = 1 min., α= .9 min., β=.01 min. and α= .4 min., β =.1 min. as a tuning parameter.

c. Disturbance Rejection (considering only disturbance):

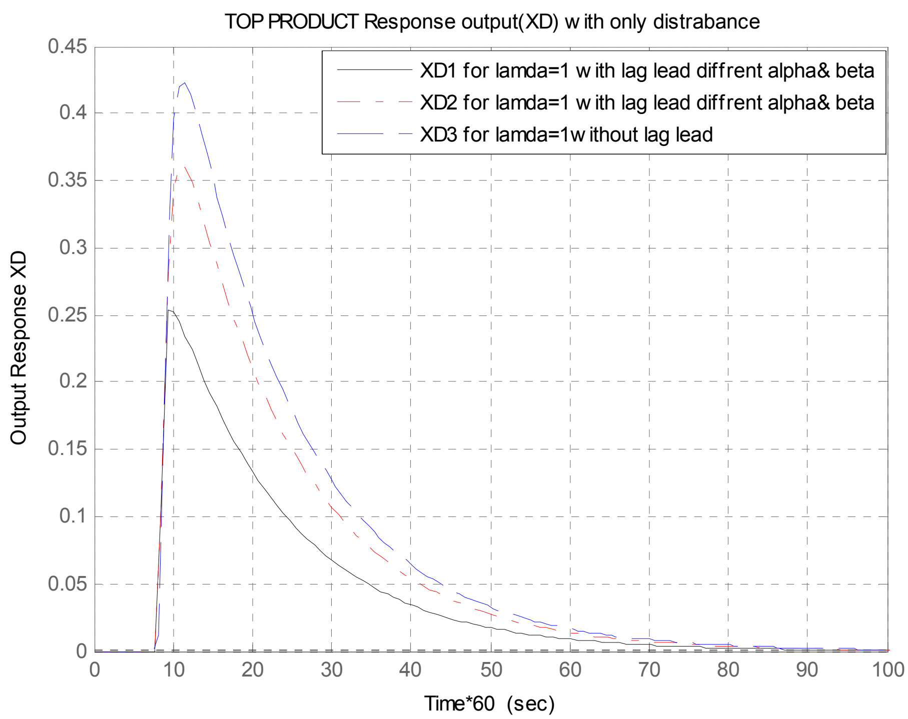

Figure5.14. Controlled variable response with only disturbance (top product X_D)

Fig.5.14 shows that using lead–lad based IMC for distillation column gives disturbance rejection up to 60-65 min. but using generalized IMC disturbance rejection taking place up to 85 min. Here I have taken λ = 1 min., α= .9 min., β=.01 min. and α= .4 min., β =.1 min. as a tuning parameter.

5.2.1. MATLAB Implementation for Bottom Product (X_B):

a. When model is perfect and no disturbance effect on the process:

Manipulated variable response (Stem flow S):

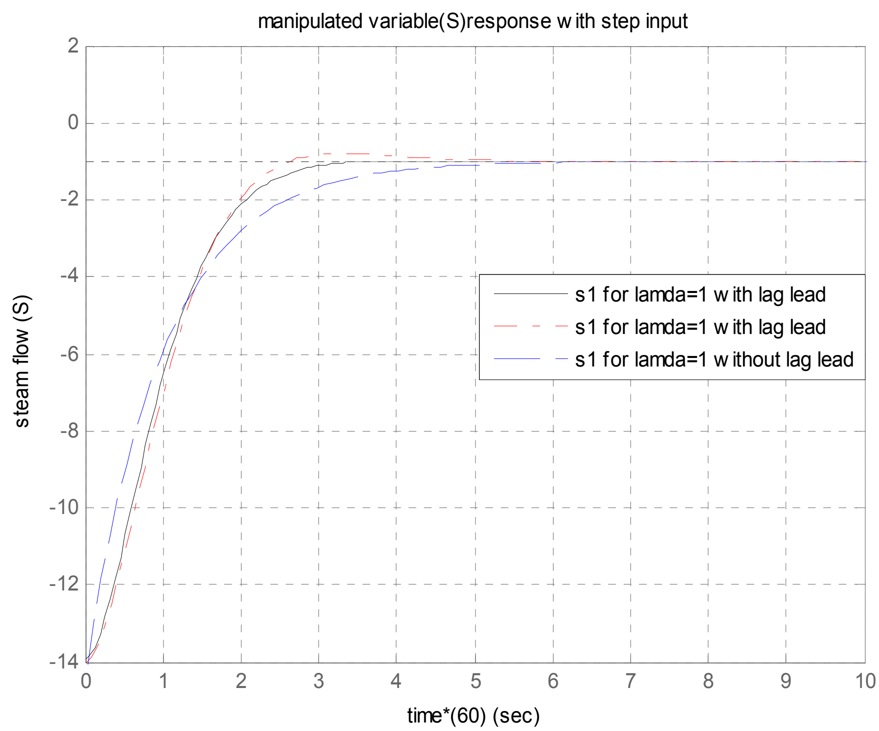

Figure 5.15 Manipulated variable response.

Fig. 5.15 shows that the rate of stem flow (s), which indicates that by using lead-lag based internal model controller response, is accurate, good set point tracking and less settling time as compare to generalize internal model controller response. The lead- lag based internal model controller response approach to critical damped but generalizes internal model controller approach to over damp.

Controlled variable response (top product X_B):

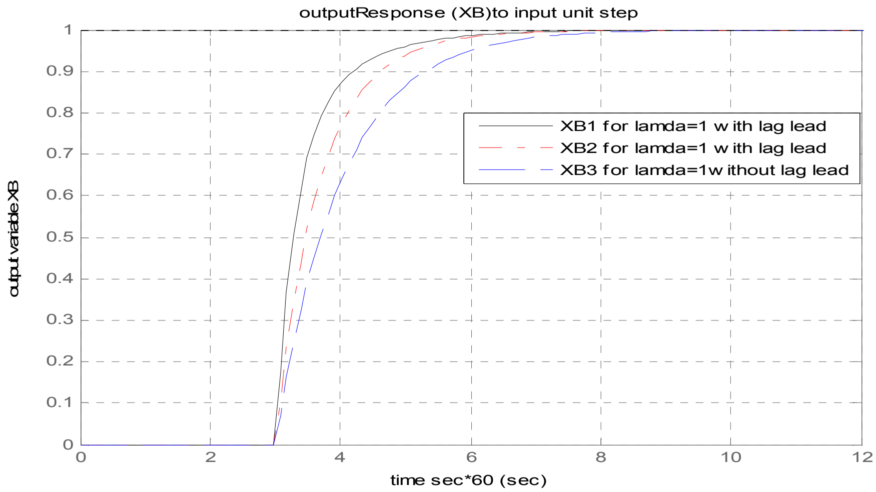

Figure 5.16 Controlled variable response (Bottom Product XB)

Fig.5.16 shows that controlled variable response X_B (bottom product) of distillation column. It indicated that with lead-lag based internal model controller output response is more accurate good set point tracking and less settling time as compare to generalize internal model controller. Here I have taken λ = 1 min., α= .8 min., β=.3 min. and α= .9 min., β =.6 min. as a tuning parameter.

b. When model is perfect and disturbance is affecting the process:

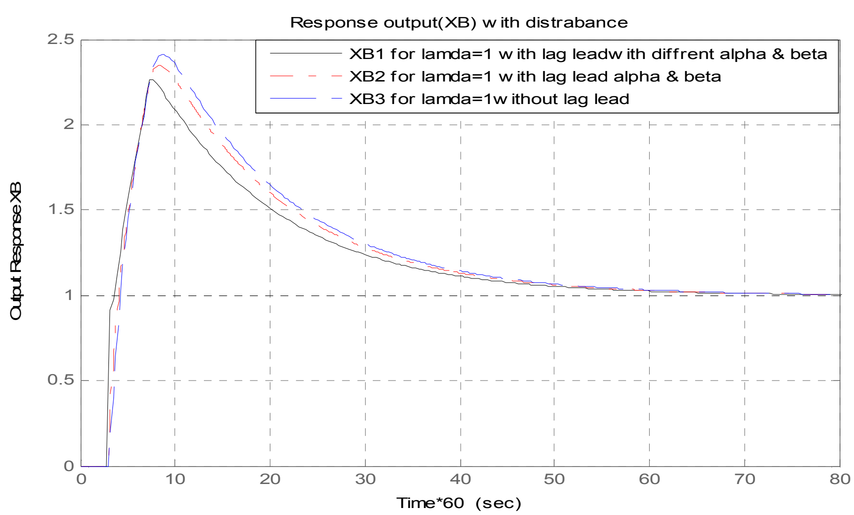

Figure 5.17 .Controlled variable response when model is perfect and with disturbance.

Fig.5.17 shows the difference between the responses of lead lag based internal model controller and generalize internal model controller. The graph shows that using lead lag based IMC for distillation column is less affected by the disturbance, here I have taken λ = 1 min., α= .9 min., β=.01 min. and α= .4 min., β =.1 min. as a tuning parameter.

c. Disturbance Rejection (considering only disturbance):

Fig. 5.18 shows the controlled variable response considering with only disturbance. We find controlled variable response using lead-lag based Internal Model Controller and with the help of this graph disturbance totally reject up to 60 minutes but using generalize Internal Model Controller response shows the disturbance reject up to 80-90 minutes. Hence lead- lag based Internal Model Control gave accurate and disturbance free response compare to generalize Internal Model Controller , here I have taken λ = 1 min., α= .9 min., β=.01 min. and α= .4 min., β =.1 min. as a tuning parameter.

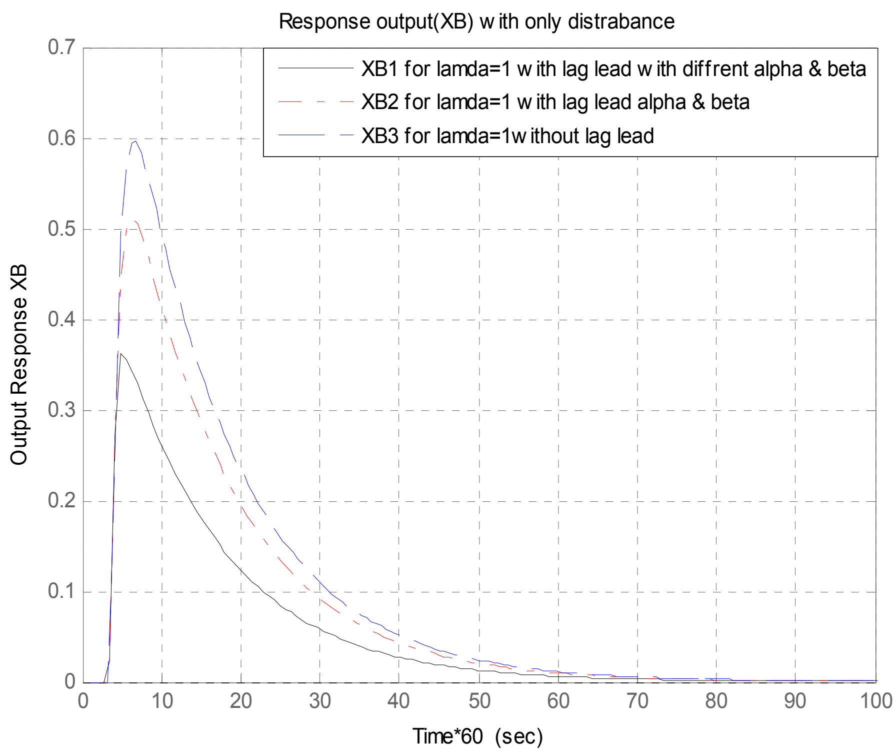

Figure5.18. Controlled variable response considering only disturbance.

5.3. Modified Internal Model Control for Binary Distillation Column:

Using equitation 5.3 and table II, I have modified internal model control response for binary distillation column. With the help of fig.4.3 and equation 4.12, 4.13, 4.14, 4.15, I got the result for K_0 , K_{imc}, K_1, K_2 and K_3.

According to reference [14] Taking step disturbance d(s) =.5 and K_0 = 1.5

$K_{imc} = \frac{(16.8s+1)}{1.5*12.8\,(\lambda s+1)} e^{-s}$ where λ we taken 3&4

K_1 = 1/0.01s+1

K_2 = -1/ K_0, hence K_2 = -1/1.5

5.3.1 MATLAB Implementation:

a. **When model is perfect and no disturbance effect on the process:**

Manipulated variable response (reflux ratio L)

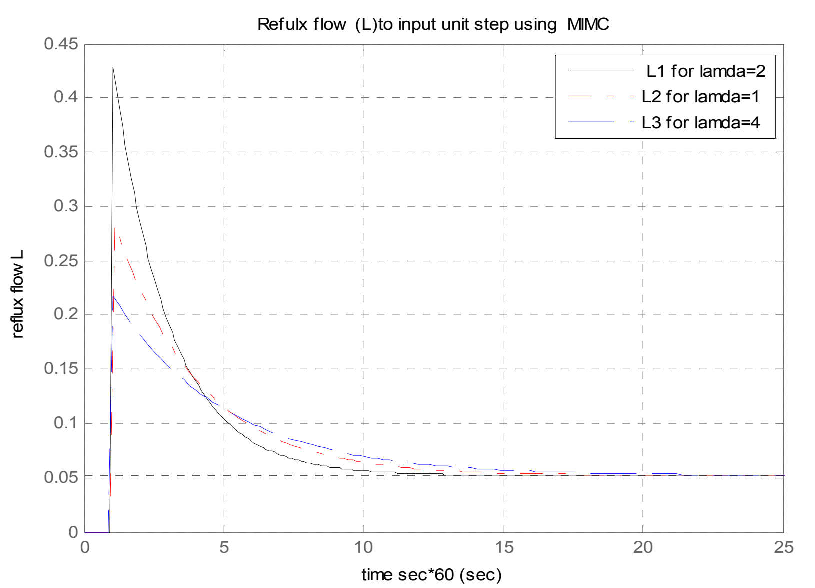

Figure5.19. Manipulated variable response (reflux flow L)

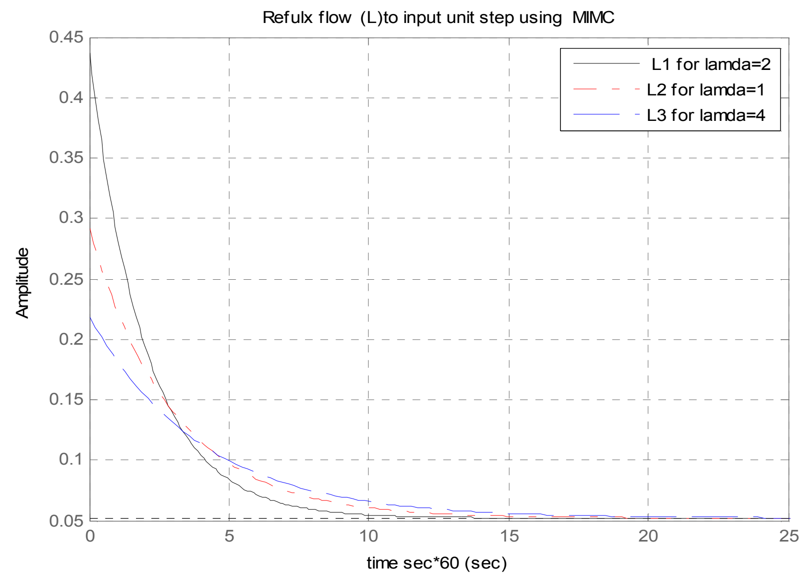

Figure5.20. Manipulated variable response (reflux flow L)

Fig 5.18 and fig.5.19 shows the manipulated variable response for Modified internal model control for different lambda (λ). fig. 5.18 indicates the response with dead time.

Controlled variable response (top product X_D):

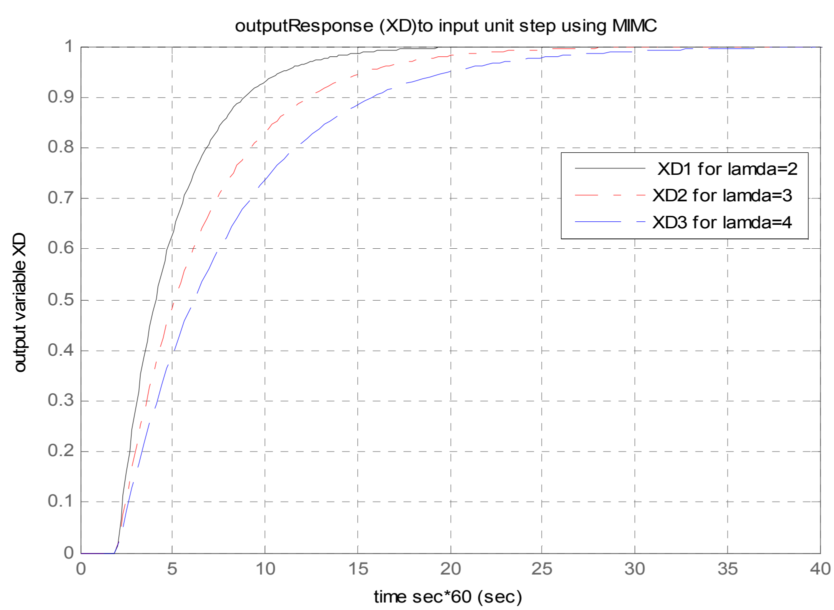

Figure5.21. controlled variable response (top product X_D)

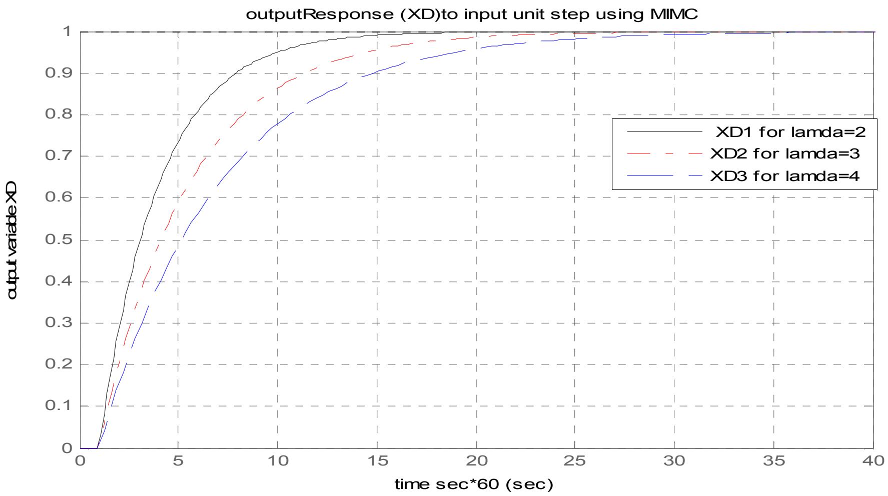

Figure5.22. controlled variable response (top product X_D)

Fig. 5.21 and fig.5.22 shows the controlled variable response using modified internal model control for binary distillation column. It gives the more accurate response compare to lead-lag and generalized internal model control response.

5.3.2 Comparison of IMC, Lead-Lag based IMC and MIMC :

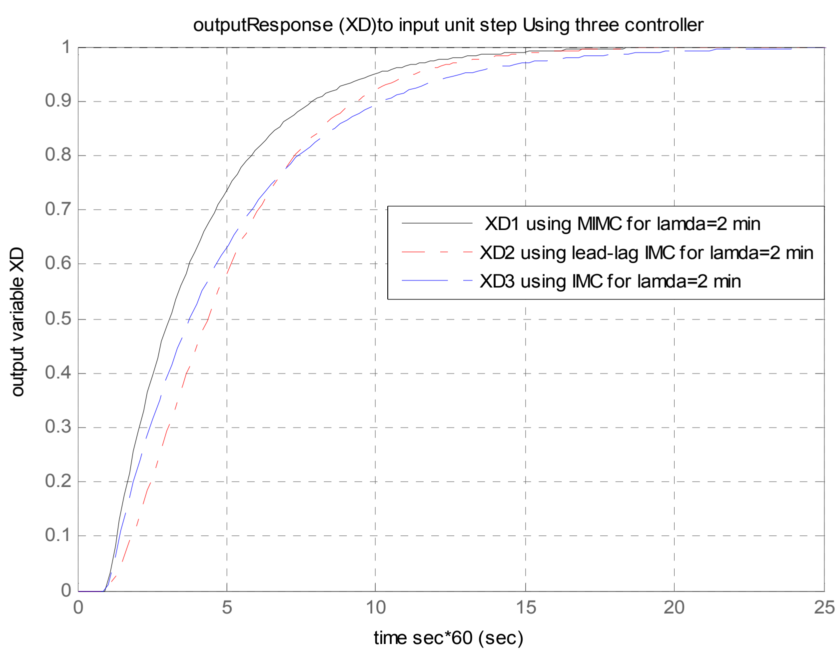

Figure5.23. controlled variable response (top product X_D)

Fig. 5.23 indicates the controlled variable response (top product X_D) for binary distillation column using three different controllers. I have taken λ=2 min. for three controllers and $\alpha = .3$ min, β = 3.33min., for lead lag based internal model control as a tuning parameter. The result shows modified internal model control gives more accurate and good set point tracking response for distillation column.

CHAPTER 6

CONCLUSION

CHAPTER 6
Conclusion

This chapter sums up the results and highlights the achievements of the research work carried out. This is followed by few suggestions for future work. The results presented in the thesis have been published by the author in different international journals and conferences.

6.1 Thesis Summary and Conclusions

In this work, I tried to implement and design Internal Model Control, Lead-Lag based Internal Model Control and Modified Internal Model control for Binary Distillation Column. For this, I have taken wood and berry process and second order process for distillation column. Using MATLAB I have implemented an internal model control response for SISO (single input single output) binary distillation column. I have also design Lead – Lag based internal model control and modified internal model control and using MATLAB find the several responses for distillation column. Comparing to generalized internal model control response lead - lag based internal model control gives good set point tracking more accurate result and less settling time for same value of λ (tuning parameter). Using lead - lag based internal model control the disturbance rejection taken palace half of the time taken by the generalized internal model control. Hence lead-lag based internal model control gave accurate and disturbance free response comparing to generalize internal model control. I have also found that modified internal model control gives more accurate result good set point tracking to controlling the distillation column. For beginning I have implemented manipulated and controlled variable for second order distillation column using MATLAB. Using internal model control there are several advantage compare to other control such as Model Predictive, control PID control, cascade control, feed forward-feedback control etc which is given below.

IMC proposed

1. Using IMC time delay compensation is achieved.
2. The filter can be used for set point tracking and disturbance rejection.

3. The controller will give offset free response at the steady state, hence steady state error must be zero.

The internal model structure distinguishes by its simplicity, in implementation and tuning. It has only one tuning parameter λ and some time the controller gain. As can be seen from the presented trends, the behaviour of the process with the proposed control system was studied for different values of the tuning parameter, observing that an increase in the gain value leads to a decrease in the transient time. The study of Internal Model Control (IMC) and its applications for design of Compensator used in IMC Model shows that our controller used is fairly robust towards uncertainty in plant parameters and it can be successfully implemented to any industrial process. The IMC design procedure can help to solve many critical problems at the industrial level. It also provides a good solution to the process with significant time delays which is actually the case with working in real time environment. As far as the tuning of the controller is concerned we have an optimum filter tuning factor λ (lambda) value which compromises the effects of discrepancies entering into the system to achieve the best performance.

6.2 Suggestions for Future Work

The following are some of the prospects for future work:

(a) Further Internal model control is design for MIMO distillation process such as 2×2 wood and berry process, 3×3 Ogunnaike and ray Distillation Process, Dokukas and Luyben 4×4 Process.[12] [13]

(b) Lead-Lag based internal model control and modified internal model control are use for several process uses in process industries given as heat exchanger system, boiler drum system, CSTR etc.

(c) Comparison between IMC based PID controller, Lead –Lag based IMC and Modified IMC is also a very good task for MIMO distillation column.

(d) IMC, Leag- lag based IMC and Modified Internal Model Control can further use for process with uncertainty (mismatch) (Robust control field) for several process.

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Dissemination

Journal:

[1] **Rakesh Kumar Mishra** and Tarun Kumar Dan , "Design a Modified Internal Model Control for Binary Distillation Column" *Journal of Instrumentation (JINST), IOP Science, May 2013*. (Communicated)

[2] **Rakesh Kumar Mishra** and Tarun Kumar Dan, "Composition Control and Disturbance Rejection of Binary Distillation Column Using Lead-Lag based Internal Model Controller", Journal of the International Measurement Confederation (IMEKO) Elsevier, May 2013. (Communicated)

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[3] **Rakesh Kumar Mishra** and Tarun Kumar Dan, "Design of an Internal Model Control for SISO Binary Distillation Column", *IEEE, ICE-CCN*, Tamilnadu, India, March 25-26, 2013. (Accepted)

[4] **Rakesh Kumar Mishra**, Rohit Khalkho, Brajesh Kumar, Tarun Kumar Dan, "Effect of Tuning Parameters of a Model Predictive Binary Distillation Column," *IEEE, ICE-CCN*, Tamilnadu, India, March 25-26, 2013. (Accepted)

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